Experimental study on water-based mud: investigate rheological and filtration properties using cupressus cones powder

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Abstract

Improper drilling fluid parameters may induce a variety of issues, including insufficient cuttings transport, limited solids suspension, poor hole cleaning, and excessive filtrate invasion to the formation. Controlled and optimized drilling fluids rheology is considered the key parameter to solve severe drilling problems encountered during drilling operations. Oil-based muds have numerous applications, but owing to some economic, environmental, and operational challenges, drilling companies are looking for new additives to enhance the characteristics of water-based muds for improved performance. However, the longer exposure of some WBM additives degrades them, which leads to insignificant mud characteristics. In this study, micro-sized naturally occurring agro-material namely cupressus cones powder (CCP) has been assessed as a potential additive in WBM for the first time to enhance the mud performance by improving its rheological and filtration properties. The objective of this study is to prepare a drilling fluid using abundantly available cupressus cones powder and investigate its effects on mud properties. The rheological and filtration characteristics of the drilling muds were determined based on API standards. A series of experiments have been performed to evaluate the impact of CCP loading on the rheology and fluid loss characteristics of drilling mud. The concentration of CCP was varied from 1 to 7 ppb. The findings of rheological characteristics demonstrated that altering the CCP loading enhanced the plastic viscosity, yield point, and gel strength of water-based drilling mud. The optimal concentration for PV was recorded in the range of 2–4 ppb, while the optimum value of YP was obtained at 6 ppb. Moreover, the temperature affected the viscosity and filtration of the mud, whereas the CCP containing muds were found salt resistant. The percent decrease in filtrate volume at 25, 121, and 150 °C was noted as 50, 59.6, and 62%, respectively. The effectiveness of the CCP was also observed from the SEM analysis. This study described the use of a locally available agro-waste material as a potential mud additive.

Keywords Agro-waste material · Water-based mud · Rheological properties · Filtration characteristics

Introduction

Drilling fluid is considered an essential component and a fundamental requirement for a successful drilling operation. Optimized drilling fluid parameters in terms of rheological and filtration properties are required to avoid any challenging

conditions during drilling (Busch et al. 2018; Agwu and Akpabio 2018; Elkatatny 2019). In a drilling operation, the mud performs several important functions, and the employed mud should have the appropriate fluid characteristics for a successful drilling operation, including suitable viscosity for suspension and reduced filtrate volume, etc. Different natural and synthetic materials have been added to the mud systems for improving the mentioned characteristics. Two broad categories of muds have been widely used including water and oil-based muds. Most of global drilling operators recommend water-based muds due to their acceptable properties, environmental impact, and lower costs (Abduo et al. 2016; Luo et al. 2017; Sheer et al. 2019). Owing to the economic, environmental, and operational concerns of oil-based muds (OBM), the drilling industry is looking for green

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and economical additives to enhance the properties of water-based mud for better performance (Mojammadi et al. 2016).

Recently, numerous agro-materials have been evaluated experimentally to be used as a cost effective and environment friendly alternatives in drilling muds for improving rheology and fluid loss control. Over time, drilling industry has shifted from using commercial polymers to agro-materials containing cellulose as filtrate loss control agents in drilling fluids. Some of the literature reported additives include but not limited to agarwood waste, rice husk, dates, grass powder, shell powder, wood powder, pistachio shell powder, mandarin peels powder, fibrous food waste material, palm tree leaves powder, green olive pits' powder, groundnut husk, psyllium husk, and date pits (Azizi et al. 2013; Okon et al. 2014; Dagde and Nmegbu 2014; Salmachi et al. 2016; Hossain and Wajheuddin 2016; Davoodi et al. 2018; Haider et al. 2019; Aggrey et al. 2019; Muhayyidin et al. 2019; Al-Hameedi et al. 2020).

Azizi et al. (2013) evaluated the efficacy of agarwood waste as a filtrate control material and compared it with a formulation containing a regular fluid loss control agent (starch). The fluid loss volume of mud containing agarwood waste and starch at standard temperature conditions was about 13 and 12 mL, respectively. In another study, rice husk showed reduced filtrate volume by nearly the same amount as PAC and CMC (Okon et al. 2014). The psyllium husk was observed to have suitable rheological properties with a concentration of 0.75–1 wt%. It was reported that psyllium husk is a potential filtrate loss control agent that reduced 13% of filtrate volume as compared to the base mud and was found more resistant to salinity (Salmachi et al. 2016). Dried grass powder in various particle sizes was mixed in WBM with different loadings. The results showed improvement in viscosity, gel strength, and filtration of the formulated mud (Hossain and Wajheuddin 2016). Experimental studies using pistachio shell powder revealed a substantial improvement in rheological characteristics, as well as a reduction in fluid loss and mud cake thickness in both LPLT and HPHT conditions. Fine particle size ($< 75 \mu\text{m}$) exhibited significant performance, resulting in a 44% decrease in filtrate volume and an improvement in rheological characteristics. Economic analysis showed 13% decline in mud cost when compared with mud consisting of polyanionic cellulose (PAC) (Davoodi et al. 2018). Dagde and Nmegbu (2014) experimentally examined groundnut husk cellulose for enhancement of filtration properties of WBM. The findings revealed that the mud containing groundnut husk had an improved pH and mud weight than the conventional mud containing PAC, which is considered a commercial fluid loss additive. Haider et al. (2019) studied the rheological and filtration behavior of WBM comprising wood powder at different percentages and sizes as an alternative to conventional polymers. The drilling fluid had enhanced rheological and

fluid loss controlling characteristics that are crucial for good functioning of oil well drilling operations. Date pit in 0.5–60 wt% was experimentally investigated as a mud additive in WBM systems. Results showed that the mud formulations could be applied in high temperature conditions. It was also found that date pit could be utilized for improving rheological and fluid loss characteristics. Non-deoiled date pit additive exhibited 40% better filtration properties than deoiled samples. Additionally, optimum filtrate loss and filtercake thickness were accomplished by adding 15–20 wt% date pit in drilling mud formulations (Adewole and Najimu 2018). A locally sourced date seed powder was used as a filtrate control agent that proved its applicability as a filtrate control additive for both fresh that salt water-based muds (Amanullah et al. 2016). Muhayyidin et al. (2019) investigated the rheological and filtration parameters of a water-based mud containing Rhizophora Mucronate tannin as a deflocculant and fluid loss additive under high pressure and high temperature (HPHT) conditions. It was discovered that it can be utilized to control filtrate loss in both LPLT and HPHT conditions.

Out of these naturally occurring agro-materials, Cupressus cones have been selected as a potential additive to improve mud properties. Cupressus Sempervirens are commonly named as Mediterranean cypress, common cypress and Italian cypress (Bounaas et al. 2019). Cypress species are categorized into three major groups: Mediterranean cypress, North American cypress, and Asian cypress. These are characterized by 25 distinct species in the Mediterranean Region, North America, and Asia (Orhan and Tumen 2015). It is an ornamental tree growing up to 45 m (150 ft) in height (Tripathi et al. 2008; Shaheen et al. 2020). Various sizes cones are grown in these trees and are considered as a waste agro-material in these countries.

In this research, the potential use of an agro-waste material (CCP) for improvement of rheological and filtration characteristics of water-based mud has been investigated. Various mud blends were prepared using abundantly available cupressus cones, and their performance was evaluated by conducting rheology and fluid loss experiments. In addition, the mud's performance was evaluated in the presence of various salt concentrations and high temperatures. This is the first study conducted to use CCP for improvement of water-based mud properties.

Materials and experimental procedure

Materials

Cupressus cones were obtained from the local trees in Quetta, Balochistan, Pakistan, which were dried and ground to micro-size using mortar grinder. Bentonite was obtained

from Sigma-Aldrich and was used as a primary viscosifier, Octanol-1, defoamer, formaldehyde and barite were provided by drilling fluids laboratory, UTP, Malaysia. Potassium hydroxide (KOH), a pH control agent, was provided by Scomi Oiltools. Deionized water was used as a continuous phase for the preparation of all mud samples.

Micro-grinding of cupressus cones

Fresh cupressus cones were obtained from trees and were kept in the oven at 80 °C for 16 h to remove the moisture. The dried cones were ground for 20 min to form micro-sized particles of CCP. After grinding, the powder was dried again in the oven at the same temperature for 12 h to obtain the powder in moisture-free form. The powder was sieved using 90- μm sieve. Sieve shaker was used to separate the ground powder into different sizes. Using weighted average, the ground CCP was most accumulated in size of 70 μm in diameter, which is a suitable size as an additive according to API specifications (API 2009). This particle size is classified as “fine” according to Table 1 particle categorization system (Idress et al. 2019). Figure 1 elaborates the entire process of CCP collection till the storage.

Table 1 Mud’s particles size classification (Idress et al. 2019)

Particle size (μm)	Particle classification
> 2000	Coarse
250–2000	Intermediate
74–250	Medium
44–74	Fine
2–44	Ultra-Fine
0–2	Colloidal

Fig. 1 Micro-grinding procedure

Table 2 WBM composition

Additive	Quantity
Deionized water, mL	350
Bentonite, ppb	15
Potassium hydroxide (KOH), ppb	0.25–0.75
Cupressus cones powder (CCP, ppb)	1–7
Barite, ppb	25
Octanol-1, mL	0.25–0.75

Drilling fluid preparation

Two sets of muds were prepared based on the temperature and salinity. In each set, 8 blends were prepared based on the composition given in Table 2. Bentonite was added with deionized water using Fann Multimixer at 11,500 rpm for 20 min to make a homogenous mixture of bentonite in water. This solution was stored for 24 h to ensure the proper hydration of bentonite. Potassium hydroxide (KOH) was added to maintain the pH in recommended limit. CCP was then added in the concentration of 1, 2, 3, 4, 5, 6, and 7 g. The addition of CCP resulted in some foam generation, which was minimized by using octanol-1 defoamer. Finally, barite was added to obtain a mud of required density. All the additives were added steadily to the continuous phase and were mixed thoroughly to ensure homogenous mixing of all the additives. To compare the current mud with a standard mud, another mud formulation consisting of commercial starch as a filtration control agent was prepared as benchmark experiment for rheological and filtration characteristics.

Performance of CCP in WBM

Density and pH of the mud

It is vital that drilling fluid could provide an acceptable weight to produce hydrostatic pressure in a wellbore and

prevent unwanted flow into the wellbore. This weight could be measured through a mud balance equipment in drilling labs. It is a fast and reliable way to determine mud density. It is important to point out that the temperature of the drilling mud has no influence on mud density determination using a mud balance.

pH meter was used to measure the pH of all the mud samples. Mud pH is a fundamental property that can influence mud characteristics such as clay dispersion, solubility, and performance of other additives.

Rheological measurements

Drilling fluids are non-Newtonian fluids, and their viscosity decreases as shear rates increase (Song et al. 2016). The most essential rheological characteristics of the drilling muds are plastic viscosity, yield point, apparent viscosity, flow behavior index, and consistency index (Luo et al. 2017; Kök and Bal 2019). Several additives are employed to enhance the rheological parameters of drilling fluids such as viscosifiers, polymers thinners, and defloculants. In this work, the mud rheological parameters were determined using Discovery HR-1 (TA Instruments). The shear rate was studied in the range of 0.01–1200 s⁻¹. Plastic viscosity, apparent viscosity, yield point, and gel strength were determined using Fann viscometer (Model: Fann 35 SA). The Bingham plastic fluid model equations (Eqs. 1, 2 and 3) were used to calculate the mentioned properties (Gbadamosi et al. 2019).

$$PV = \theta_{600} - \theta_{300} \quad (1)$$

$$YP = \theta_{300} - PV \quad (2)$$

$$AV = \frac{1}{2}\theta_{600} \quad (3)$$

where, θ_{300} and θ_{600} are the dial reading at 300 and 600 rpm, respectively. AV represents the apparent viscosity; PV is plastic viscosity and YP is the yield point.

For gel strength determination, the API recommended procedure was followed by stirring the mud sample at 600 RPM for 10 s to ensure proper dispersion. Then, the sample was brought to static conditions for 10 s followed by stirring at 3 RPM. The 10 s-gel strength was measured by the highest deflection on the viscometer. The same was repeated for 10 min gel strength by keeping the sample static for 10 min.

Filtration measurements

The LPLT filtration experiments at static conditions were performed through a conventional API filter press (Fann) with a controlled nitrogen pressurizing system. The standard

API filter with pore size varying from 25 to 30 μm was used as filter media to accumulate the filtercake. The measurements were performed at room temperature and 100 psi pressure according to the API recommended standard procedures to examine the filtrate control capability of CCP containing drilling muds. For HPHT filtration, the samples were exposed to 121 and 150 °C at a constant pressure of 400 psi using Ofite mud filtration system. The filtrate volume against standard time (30 min) was measured, and finally, the filtercake thickness of each sample was measured after completion of experiments using a digital vernier calliper.

Salt and temperature resistance tests

A water-based mud's characteristics, including density, rheology, and filtration, are more susceptible to salt contamination and temperature variations. The measurements may need understanding about salt resistance and temperature impacts on the mud additives used (Oseh et al. 2019). Here, 4 ppb of CCP and various concentrations of NaCl (2, 4 and 6 M NaCl) were tested and reported.

The thermal stability of mud blends was evaluated after subjecting them to high temperatures (121 and 150 °C) in a hot roll oven for 16 h. The mud properties were again tested using Fann viscometer. Likewise, the combined effect of salt addition and hot roll temperature on mud rheology and filtrate volume was evaluated and reported.

Results and discussion

Density and pH of the mud

Drilling mud density is an important parameter which could provide an acceptable weight to produce hydrostatic pressure in a wellbore and prevent unwanted flow into the wellbore. The mud weight of the studied samples is given in Fig. 2a. It is observed that the density was first rose with the increase in the CCP loading, then started declining. The base mud showed a mud weight of 8.65 ppg, while the commercial starch sample showed 8.9 ppg. With further increase in the CCP amount resulted the decrease (after 2 ppb of CCP). The reason of this reduction is due to the foam formation in the mud which lowered the overall mud weight of the system. Finally, the CCP 7 sample showed the lowest mud weight in the studied range which is a decrease of 2.89%.

Similarly, the pH results of the current mud samples are given in Fig. 2b. From the experimental results, it was found that all the muds showed pH values above 9.0. The amount of CCP slightly affected the pH of the mud because of minor increase in OH⁻ ions of the potassium hydroxide (KOH) in the presence of the CCP. The base mud showed a pH of 9.09 while the highest pH was observed as 9.23 by sample

Fig. 2 a Mud weight and b pH of the studied muds

Table 3 Statistical data for studied mud blends

Mud blend	Shear stress, γ	Consistency index, K	Flow behavior index, n	n Standard Error	Adj. R-square
BF	0	1.64571	0.39835	0.02008	0.99796
CCP 1	0.24534	2.69948	0.3329	0.00916	0.99951
CCP 2	2.28528	2.26049	0.35586	0.01617	0.99854
CCP 3	3.1887	2.16987	0.36625	0.01125	0.99931
CCP 4	5.16053	1.78848	0.39169	0.01189	0.99926
CCP 5	8.94869	1.10587	0.47303	0.02321	0.99759
CS	7.94072	1.78541	0.41711	0.02185	0.99762
CCP 6	11.99948	0.91222	0.52322	0.02431	0.9976
CCP 7	12.89946	0.91026	0.52317	0.01804	0.99868

containing 6 ppb of CCP. This is attributed to an increase of 1.54%. On the other hand, the pH of the sample containing commercial starch was noted as 9.19. The pH of all the samples is almost comparable with the API recommended values.

Rheological properties

Numerous models have been used to describe the behavior of non-Newtonian drilling fluids including Bingham Plastic, Power Law, Hershal Bulkley and Heinz–Casson and Carreau model. The current mud blends were fitted with the available rheology models, and the best fitted model parameters have been reported (Table 3). It has been noticed that for the base fluid, the most suitable model was Power Law model which showed 0 yield stress while the other blends best fitted with the Hershal Bulkley model. When the results were compared with the commercial starch (CS), it revealed that the rheogram of the commercial starch lies between the CCP 5

Fig. 3 Stress-shear rate behavior of the studied muds

and CCP 6 (Fig. 3). It can also be observed from the studied samples that the yield stress is going to be increased with the addition of CCP showing an improved cuttings transport capability of the studied mud. The higher dosage of CCP could require more stress and thus considered to be avoided because of increased load on the pumps during cuttings transportation. When the consistency index values of the studied muds were compared, it was found that the commercial starch and CCP 4 showing almost similar results. It could also be observed from the flow behavior index values for the same samples. The standard error was quite low showing the adequacy of the fitted data, which could also be seen in the R squared values.

The rheological parameters such as plastic viscosity, yield point, and gel strength of non-Newtonian drilling muds can be measured in the petroleum industry using the Bingham Plastic model equations. In this study, these parameters were

quantified at room temperature and at atmospheric pressure (0.1 MPa) using a rotational viscometer at various concentrations of CCP. The findings of rheological tests performed on drilling fluid samples incorporating CCP are shown in Fig. 4. From Fig. 4a, it is noticed that the apparent viscosity of the base mud without CCP was 16 cP while the CCP 6 and CCP 7 resulted AV as 32 cP. This increase in AV is due to the amount of CCP addition that resulted the rise in friction between the particles and restricted the particles movement. In addition, it could be because of the comparatively higher specific surface area to volume ratio and smaller size of the CCP. In drilling operations, an acceptable range of viscosity is demanded for the required circulation of drilled solids.

Plastic viscosity is one of the key parameters in the Bingham model which depicts drilling mud viscosity. Figure 4b displays the response of plastic viscosity with the addition

Fig. 4 a Apparent viscosity, b Plastic viscosity, c Yield point and d Gel strength of the mud samples

of CCP. The CCP concentration improved the PV because of the addition of more solid content into the base fluid which creates resistance to flow. The highest PV value was recorded for CCP 6 and CCP 7, whereas all the obtained values are in the recommended range of API. The optimal concentration in the current study was recorded in the range of 2–4 ppb because higher than 4 ppb, the value of PV rises more which can cause extra load on the circulating pumps. Hence, this value should be kept in optimal range recommended by API to avoid the excess load on the pumps.

Another significant characteristic in fluid flow is the yield point, which is determined by electrostatic forces among mud particles. It is an attractive force among colloidal particles in drilling mud required to transport drilled solids and enhance the efficiency of hole cleaning. It is regarded to be a crucial indication of a mud system's capacity to remove cuttings out of the hole. During the drilling operation, an appropriate yield point value is required to carry the drilled cuttings while preventing excessive pressure on the mud pumps. The findings of the current study are given in Fig. 4c. It has been observed that the yield point of the base and CS fluid has 18 and 23 lb/100 ft², respectively. However, with the increase in the CCP amount in the mud showing an increasing trend which is in accordance with the previous studies. This shows that the mud is capable of carrying cuttings from the borehole to the surface effectively. This increase is attributed to the fact that the strong electrostatic excretion exists between mud particles with negative ions. These ions result to develop a stable and homogenous phase in the system. The maximum value of yield point was quantified as 33 lb/100 ft² with the addition of 7 ppb of CCP. In conclusion, CCP was found as a suitable additive for yield point improvement when compared with base mud.

Gel strength is a measure of the shear stress required to initiate a fluid flow that has been dormant for some time. This keeps the solid particles of mud in suspension while the circulation is ceased and not letting the solids to drop down to the bottom which creates further issues with the bit and other assemblies. When the gel strength of the studied mud samples was compared with the base and CCP mud, the findings showed an improvement with the addition of CCP. The highest GS values both for 10 s and 10 min were found at 4 ppb of CCP concentration. It was also observed that the CS mud showed almost similar behavior as shown by CCP 1. It shows that the CCP can develop a gel structure in the presence of bentonite even at a lower concentration.

Thermal stability

It is known that the increase in temperature can cause a reduction in the fluid viscosity due to the breaking of the developed network. While drilling a well, the muds are exposed to higher temperatures for a longer time which

Fig. 5 Plastic viscosity at 25, 121, and 150 °C

reduces the efficiency of the mud. To mimic the wellbore temperature and pressure conditions, the mud samples were kept for 16 h in hot roll oven at the mentioned temperature conditions (121 and 150 °C). The effect of the temperature was observed and recorded in Fig. 5. The optimum concentration for 121 °C was found in the range of 4–7 ppb, whereas the highest PV was recorded as 11 at 150 °C. Overall, at 150 °C, the PV remained very low because of the disintegration of bonds between bentonite and CCP particles. However, the results are considered significant and can reduce the extra load on the pumps during mud circulation. On the other hand, the mud containing CS is depicting almost similar behavior as shown by mud containing 5 ppb of CCP.

Filtration properties

The filtration characteristics of the current muds are given in Fig. 6a and b. The addition of CCP showed improved performance in terms of reducing the filtrate volume as well as the cake thickness. It is a key factor to be considered because the filtrate can cause numerous irreversible changes in the exposed rocks. The CCP showed promising results when added as a filtrate control agent in bentonite-based mud system. At 25 °C, the highest fluid loss was recorded by 1 ppb of CCP, while the lowest volume was recorded by 5 ppb. Increasing more than 5 ppb caused irregular-shaped filtercake that resulted in higher fluid losses.

Similarly, at 121 °C, the increase in CCP showed a reduction in fluid volume and the lowest volume was recorded at 7 ppb. Moreover, it is noted that the filtrate volume reduction stabilizes after 5 ppb of CCP as almost the same values can be seen for 5, 6, and 7 ppb. The commercial starch

Fig. 6 **a** Fluid loss and **b** filtercake thickness of muds

showed better results in all the cases. It could be due to the soluble contents in the commercial starch which increased the viscosity significantly and thus, kept the solid particles in suspension. At 150 °C, the filtrate volume was increased when compared with the standard and 121 °C conditions. The lowest fluid loss volume was recorded at 7 ppb, but still the volume was more than the API recommended range (API 2009).

Another important factor in mud filtration is the formation of filtercake on the borehole wall. In all the mud blends containing CCP, the filtercake thickness was decreased with the addition of CCP as shown in Fig. 6b. The base fluid revealed a thick filtercake while the addition of CCP reduced the thickness significantly. This was because of the plugging of the pores which further reduced the fluid loss and hence reduced the thickness. Overall, the filtration properties of mud were improved and CCP was found a suitable additive for filtration control.

The SEM micrographs of the filtercakes generated from the lowest and highest fluid loss volume are given

in Fig. 7. It is clear from the images that the visible void spaces can be seen in the filtercake containing 1 ppb of CCP. On the other hand, the proper network has been developed by bentonite and CCP and kept minimum void spaces in CCP 7.

In Fig. 8a, b and c, the relationship between the PV and filtrate volume has been shown. Generally, it was observed that the filtrate volume reduced when the plastic viscosity of the mud was increased. This is due to the rise in resistance in the flow, which restricted the fluid loss.

Effect of salt concentration

The effect of salt concentration in the presence of high temperature of the hot roll was studied on the optimized mud sample and recorded in Fig. 9. Figure 9a shows that the salt content had a minor impact on the plastic viscosity at room temperature. No significant changes have been recorded in plastic viscosity when 2 M NaCl was added. However, at 121 and 150 °C, the PV was reduced in the presence of

Fig. 7 SEM micrograms of filtercakes **a** CCP 1 and **b** CCP 7

Fig. 8 3D color map of PV, CCP and filtrate volume at **a** 25 °C, **b** 121 °C and **c** 150 °C

Fig. 9 Combined effect of salt and temperature on **a** plastic viscosity and **b** fluid loss

sodium chloride ≥ 2 M NaCl. No significant change has been observed with the addition of salt ≥ 2 M NaCl. This shows the effectiveness of the CCP, that it is resistant to higher salt concentrations. Although, the decrease in PV was observed due to the long exposure to the high temperatures.

Similarly, the fluid loss volume has also shown the same behavior with the addition of salt in the presence of high temperature. Overall, the salt addition did not show any adverse effects on the properties of mud. Overall, the impact of all the rheological and filtration characteristics was enhanced with the utilization of the cupressus cones powder. Although some of the filtration tests in higher temperature conditions resulted in higher volumes, but at ambient and 121 °C temperature, very promising results were obtained. The most valuable property of this additive is its salt resistance which is very important because the higher salt concentration can break the bonds between the clay and other additives which further leads to insignificant mud characteristics. Owing to the availability and better performance of the CCP, it could be utilized as a rheology enhancer and well as the filtration loss reducing agent. Moreover, the biodegradability, thermal stability and salt resistance capability of CCP make it an appropriate mud additive. The findings showed significant improvements in mud performance when compared with the commercial starch. Thus, the applications of this natural additive could be extended to field scales.

Conclusions

Based on the current experimental study, it was concluded that micronized cupressus cones, which is considered a waste material can be utilized as an effective agent in water-based mud system for the improvement of rheological and filtration characteristics both at ambient and higher temperature conditions. The pH of mud samples was found in API recommended range. Mud weight of the samples showed a decrease after 2 ppb CCP because of foam formation. The optimal concentration for PV was recorded in the range of 2–4 ppb, while the optimum value of YP was obtained at 6 ppb. The gel strength and AV were also enhanced by adding CCP in the base mud. The temperature affected the viscosity and filtration of the mud, whereas the CCP containing muds were found salt resistant. The percent decrease in filtrate volume at 25, 121, and 150 °C was noted as 50, 59.6, and 62%, respectively. The effectiveness of the CCP was also observed from the SEM images. It is further recommended to investigate the effect of nano- and other mixed sized CCP on the mud properties. Moreover, the thermal and detailed microscopic analysis of filtercakes is required to understand in depth about the plugging mechanism of micronized CCP.

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Declarations

Conflict of interest The authors declare that there is no conflict of interest.

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